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WIND ENERGY

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16. Abstract

The technical and economic problems involved in the use of wind engines as a source of power are discussed, with detailed descriptions of the operative principles behind several basic types.

Solutions have already been found to the technical problems involved in producing small amounts of power, and problems remain only in the area of high power production. The solution to the economic problems involved depends on mass production, which presupposes the design of a prototype, and so far no country has accomplished this type of project. Offsetting these apparently pessimistic conclusions is the fact that wind engine theory has been thoroughly developed, thus clearing the way for broader research, assuming that a given country or organization will be willing and able to provide the necessary capital.

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WIND ENERGY

G. Lacroix

I. General Remarks

Among the natural forces susceptible to human use, wind is characterized by the fact that its energy can easily be captured by simple -- even rudimentary -- methods, while its available power is low; consequently the design of high-power wind engines raises difficulties which have yet to be solved completely. In the past, moreover, the sole applications to which this energy source has been adaptable, such as the use of pumps or windmills, have required energy of little more than ten horsepower. This perhaps explains why wind engine design has for a long time been limited to the reproduction of tested models of mediocre power output, represented at each extreme by the four-blade Dutch windmill, with a blade diameter of not more than 25 meters, and the American windmill, used primarily for irrigation, with a diameter which seldom reaches ten meters. /77*

Fairly recently, the production of electrical energy began to offer a new and very important field of application for wind engines. The first installations, which were usually created simply by adding a dynamo to an existing windmill, quickly demonstrated the importance of some means of energy accumulation to assure a continuous supply of electrical current from an autonomous installation, even during periods of calm or low wind. The initial and maintenance costs for storage batteries (or heat engine standby units) have a heavy effect on the cost price of the current, and it was soon proposed that all means of energy accumulation be eliminated, with continuity of service to be assured simply by connecting the wind generator in parallel with a public

* Numbers in the margin indicate pagination in the foreign text.

electrical network. Since such a network would be capable of consuming large amounts of power, the idea naturally arose that actual "aeroelectric" plants might be built to supply the network, like the other thermal and hydroelectric plants. Installations producing power on the order of one thousand kilowatts have been projected or constructed in other countries. The current fuel shortage has only increased the already existing interest in such installations in France, and various official or private initiatives now offer the prospect that the use of wind energy may soon enter a more active phase. It therefore might be useful at this point to make a brief review of the various methods of capturing wind energy which may be projected under current technical conditions, and to discuss their respective advantages and disadvantages.

At first glance the most striking characteristic of wind energy is its extreme abundance, combined with a low density. Wind exists everywhere, at least intermittently, and consequently this natural force might be considered an inexhaustible energy source. As an illustration it may be noted that if it were possible to install wind engines in our national territory (600,000 km^2) at the same density as that which has already been attained in Flanders (and which was not unusual elsewhere in the past, as indicated by old engravings), that is, ten 10-kW wind engines per square meter, the total power produced could be as high as 60,000,000 kW, a figure much higher than that produced by harnessing the power from all our waterways (8 to 9 million kW). This tremendous amount of energy, however, is distributed in the air at an extremely low density. By reason of its relatively low specific weight (1.25 kg/m^3) that is, 1/800th that of water), an air current is able to supply only 1/800th the power obtainable from a water current at the same speed. Consequently the production of power in any quantity implies the use of extremely high rates of air flow, that is, the design of extremely wide-span devices which are difficult to protect from high winds. As an example, the production of an operating power of 40 kW using the moderate winds available in France (6 m/sec) requires a wind engine 30 meters in diameter using an air flow rate of 3200 m^3/sec. To offset this disadvantage, however, wind energy, in contrast to water energy, offers the advantage of universal availability without requiring civil engineering projects such as dams, canals, etc. Thus the higher cost of the machinery itself due to its large size is more than compensated by a nearly total elimination of contruction projects necessary for its use.

II. Study of Various Types of Machines

All machines designed to capture wind energy act by decreasing the speed of the wind by opposing its flow with suitably arranged movable surfaces. Because of this decrease in speed the air loses part of its kinetic energy, and the energy freed in this way is translated into a force or thrust applied to the movable surfaces which can be used to produce a useful effect, such as propulsion of a ship or vehicle, production of horsepower, etc. Wind engines may be divided into two broad classes according to the manner in which the movable surfaces are displaced in relation to the wind.

Panemones

The first class includes devices whose movable surfaces are arranged perpendicular to the wind and which move in the direction of the wind. The simplest example of this type is a ship sailing before the wind. Schematically it may be constructed like the devices shown in Fig. 1, where a flat wing with a surface area S, mounted on a carrier, is subjected to the action of wind at a speed V, striking the surface perpendicularly. When the surface S is immobile, the wind exerts on it a force which experimentation has shown to be proportional to the surface area S, to the wind speed squared, and to the specific weight ρ of the air:

$$F = k\rho S V^2$$

Customarily these equations use the quantity /78

$$\frac{1}{2}\rho V^2$$

or stagnation-point pressure, which corresponds to the dynamic pressure measured with a Pitot tube in an air current at a speed V, with the result that the force F can be written:

$$F = C_T\ S\ \frac{1}{2}\ \rho\ V^2$$

The coefficient of thrust C_T depends on the shape, the composition, and, to a certain extent, the dimensions of the surface. Various investigators have determined the value of this coefficient for the most common surface shapes.

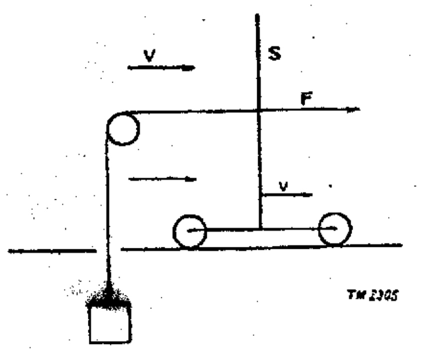

Fig. 1. Action of wind on a surface S perpendicular to its speed V.

If the carrier is free to move, it begins to travel in the direction of the wind, activated by the force F, and the latter may be used to produce useful work, for example to lift a weight (Fig. 2). However, the relative speed of the wind in relation to the surface decreases, as does the force F. If v denotes the speed of the surface S, the relative wind speed is no greater than $V-v$ and the force becomes

$$F' = C_T\ S\ \frac{1}{2}\ \rho\ (V-v)^2$$

The operative power supplied, produced from the force F' over the path traveled v within a given time unit is

$$W = F'v = C_T\ S\ \frac{1}{2}\ \rho (V-v)^2 v;$$

This power is at its maximum for $v = \frac{V}{3}$, that is, when the speed of the movable surfaces is one-third that of the wind. The value of the power is therefore:

$$W_{max} = \frac{4}{27} C_T \frac{1}{2} \rho S V^3.$$

The power supplied by the wind is, moreover, $W' = F'V$, since the air moves at a speed V and exerts a force F' in the direction of its movement. It can thus be seen that under the most favorable conditions where $v = \frac{V}{3}$, wind engines based on this principle cannot be expected to capture more than one-third of the wind energy available. The other two-thirds are dissipated as heat losses in vortices which originate behind the movable surfaces, or this energy may be included in the kinetic energy of the air circulating around the surface.

Obviously the concept of efficiency does not have the same importance for wind engines as it does for other machines. Since wind is available in unlimited quantities, the essential engineering problem is not so much to produce a certain power with satisfactory efficiency as to produce this power at the lowest cost price. Thus the low efficiency (maximum 33%) of wind engines with movable surfaces struck perpendicularly by the wind would not be an adequate reason to discount this class of devices a priori. The low value of this efficiency, however, offers the possibility that wind energy might be better used by reducing the vortices produced, by arranging the movable surfaces in a more judicious manner. It will subsequently be shown that this is indeed the case.

In addition, wind engines of this type have two further drawbacks. First, the speed of the movable surfaces must always be lower than that of the wind. Wind engines thus operate at low speeds, and large and costly multiplying gear trains are necessary for them to drive electrical generators. Furthermore, the movable surfaces cannot travel indefinitely in the direction of the wind. When they have reached the limits of their movement they must be removed from the action of the wind and returned to their original positions. This return movement is accompanied by considerable power losses and a proportionate loss in efficiency, even if the movable surfaces are positioned so as to be in profile to the wind.

These wind engines, which are generally termed "panemones," consist in practice of a paddle-wheel rotating around a vertical axis. It is obvious that the power consumed by the blades moving in reverse direction to the wind must be less than the power generated by those moving in the wind direction. For this reason, a screen in the form of a half-cylinder may be arranged around the wheel to shield the blades during their return movement, thus removing them from the effect of the wind (Fig. 2a). This screen may be moved either manually or by means of a vane, in such a way that it will continue to operate accurately in spite of changes in wind orientation. The screen also makes it possible to regulate the operating power of the wind engine by covering, more or less completely, the drive blades which are struck by the wind. Another solution consists in giving the blades a concave cylindrical shape. It has been experimentally shown that the thrust coefficient of such surfaces is much lower when they are struck by the wind on their convex side rather than their concave side. Thus panemones such as those shown in Figs. 2b and 2c, consisting of a simple metal sheet bent into an S-shape, are set in motion by the asymmetry of their blades, without the necessity for a screen to shield part of them from the wind.

A Finnish inventor, Sevonius, originated the idea of perfecting the device shown in Fig. 2c by mounting the two shells of which it is composed so that a space is left between them, as shown in Fig. 2d, rather than placing them end to end. In this way, the blade which moves in a reverse direction to the wind receives a supplementary thrust on its concave surface due to the wind transmitted to it by the other blade, and the useful effect is proportionately increased.

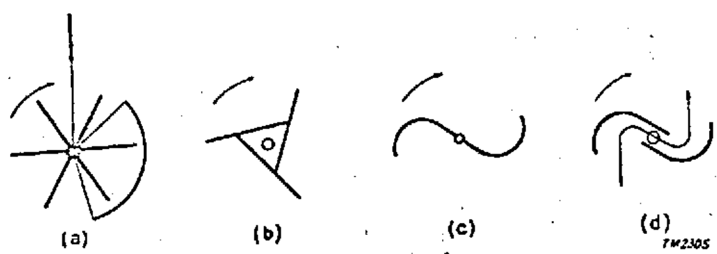

Fig. 2. Classical examples of panemones with fixed blades: (a) with shield adjusted by vane; (b) and (c),with asymmetric blades; (d) Sevonius rotor.

A more effective procedure consists in articulating the blades in such a way that they will turn aside during the part of their rotation in which they are moving against the wind. For this purpose they are made to move around vertical (Fig. 3a) or horizontal axes (Fig. 3b) and they are automatically bent back by the wind pressure at the end of their useful movement. A number of variations on these configurations have been proposed. /79 All of them entail the disadvantage of using central shafts which are difficult to maintain and lubricate, thus eliminating their simplicity; and they also entail the important disadvantage of producing shocks each time the movable surfaces strike their respective stops.

In more improved models, the rotation of the blades around their vertical axis is controlled by means of a suitable control linkage (the simplest being a control system using chains and gears, as in Fig. 4), and rotation occurs at half the speed of the panemone. A blade moving upstream is in retracted position, while those at *a* and *b* are in an oblique position in relation to the wind, inclined in such a way that they participate in the production of energy. This type of device thus constitutes a transition between panemones strictly speaking and the devices which will be studied below, where wind acts by reaction on oblique surfaces.

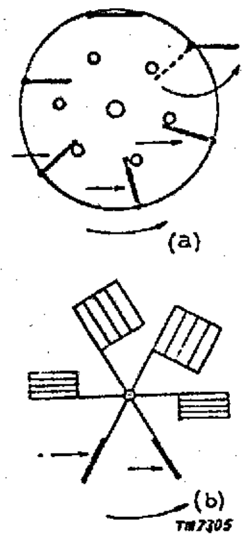

Fig. 3. Examples of panemones with blades which fold back spontaneously under the action of the wind: (a) individually, around vertical axes; (b) in pairs, around horizontal axes.

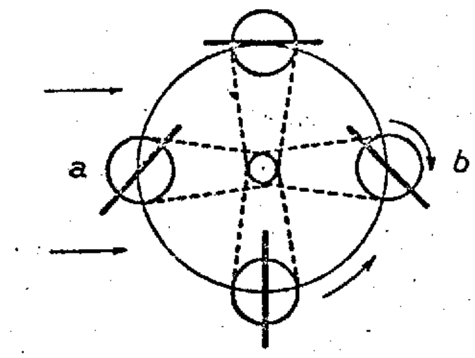

Fig. 4. Panemone with retraction controlled by chains and pinions.

No matter what configuration is used, it will be impossible for the speed of the blades to satisfy at all points the condition $v = V/3$ which would result in maximum efficiency. The actual efficiency of panemones is thus much lower than the maximum efficiency, which itself is very low. This type of wind engine thus necessitates a large surface area if any appreciable power output is desired. However, the surface area which can be constructed in practice is limited for economic reasons, since the effects of high winds must be taken into account. In actual fact, panemones, including the Savonius rotors, which appear to be the most highly developed type, have only very rarely been constructed with surface areas greater than ten square meters, and the power produced has never exceeded a few horsepower under moderate winds.

This type of wind engine thus does not appear to be particularly well suited to construction of the high-power installations which are currently being projected. Its advantages, on the other hand -- simplicity, durability and ability to operate independently of wind orientation, -- make it readily adaptable to certain applications, such as low-power installations or vehicle ventilation.

Turbines

The poor efficiency of panemones is due to the fact that the motive force F moves in the direction of the relative speed $V-v$. One might consider whether better efficiency might be obtained with surfaces for which the force F would make a given angle with the relative speed $V-v$, since the energy loss would not be more than ${}_1F(V-v)\cos\alpha$. Experiments have shown that this result may be obtained by using a surface which, instead of being perpendicular to the relative wind as in panemones, make a given angle with it which is generally small.

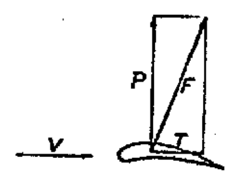

Fig. 5. Wind action on a fixed surface inclined in relation to its speed V.

In Fig. 5, this surface is represented in the the form of a streamlined airfoil analogous to an airplane wing, but the reasoning would be the same if the surface had any other shape, for example that of a plane or a trough formed into a circle. When such a surface is placed at a low pitch (or angle of attack), in an air current at a speed V, the force F is no longer in the direction of the speed V as it was previously, but forms with the latter an angle of nearly 90°. This force may be broken down into two forces, L or lift, perpendicular to the speed V, and D or drag, parallel to the speed. The latter, which also measures the resistance to forward motion of the airfoil afforded by the internal part of the fluid, corresponds to an energy dissipation $D \cdot V$ in the form of vortices in the wake. Component L necessitates no consumption of energy since it is perpendicular to the direction of movement. Its only effect is to modify the direction of the wind without changing its energy.

In order to produce considerable force with a low expenditure of energy, one need only use airfoil profiles for which force L is as large as possible and force D as small as possible. An airfoil is characterized by its aerodynamic efficiency, which is the ratio L/D. The best airfoils used in aviation currently attain an aerodynamic efficiency of 50, and it is even possible to reach 100, which would mean that a glider released at a height of 1 km could theoretically fly for 100 km before landing.

It should also be noted that the two forces L and D are commonly expressed as a function of the surface area S and the stagnation-point pressure $1/2\ \rho\ V^2$ by the two equations:

$$L = C_L \frac{1}{2} \rho\ V^2\ S$$

$$D = C_D \frac{1}{2} \rho\ V^2\ S$$

in which C_L and C_D designate two coefficients (lift coefficient and drag coefficient) which must be determined experimentally for each profile, and which vary, furthermore, with the angle of attack. The surface area S used in these formulas is not the surface area measured perpendicular to the direction of the wind, as one might first assume, but rather the actual surface area of the wing, the product of its width (or depth) and its span.

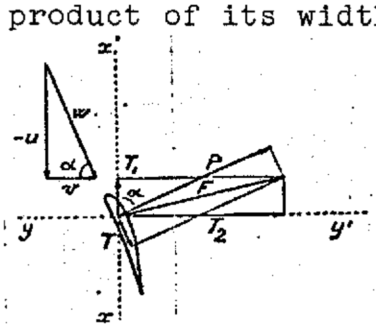

Fig. 6. Wind action on a movable surface moving perpendicular to its speed V.

The second large class of wind engines thus includes devices in which the drive surfaces are struck at an acute angle by the relative wind. The simplest type, which corresponds to a ship sailing under a lateral wind, is that of an airfoil surface moving perpendicular to the wind at a speed u (Fig. 6). We will use v to designate the speed of the wind near the surface, since it will subsequently be shown that this speed is not equal to the speed V of the wind at a large distance from the wind engine, but is always lower than V. The relative wind which strikes the

surface travels at a speed w resulting from a combination of the speed v of the wind and the speed $-u$ of the wind in relation to /80
the surface. This speed w makes an angle α with that of the wind such that

$$\tan \alpha = \frac{u}{v}$$

As in the preceding, the thrust produced by the action of the wind can be broken down into lift L and drag D, and it can easily be seen that L also forms an angle α with the speed u. The motive force T_1 in the direction of movement of the surface is obviously equal to the difference between the projections of the two forces L and D along a line xx', while the thrust T_2 exerted in the direction of the wind is equal to the sum of the projections of these two forces on yy':

$$T_1 = L \cos \alpha - T \sin \alpha = L \cos \alpha(1 - a \tan \alpha)$$

$$T_2 = L \sin \alpha + T \cos \alpha = L \sin \alpha(1 + a \cot \alpha)$$

a denoting the inverse of the aerodynamic efficiency, that is the ratio D/L.

The operative power is $T_1 u$, while that lost by the wind is $T_2 v$. Noting that $v \sin \alpha = u \cos \alpha$, the efficiency of the wind engine is therefore

$$\eta = \frac{1 - a \tan \alpha}{1 + a \cot \alpha} = \frac{1 - a\frac{u}{v}}{1 + a\frac{v}{u}}$$

With a perfect airfoil profile without drag, for which a would be nil, the efficiency would thus be equal to unity and the energy transformation would be effectuated without losses. The profiles which are usable in practice correspond to a very low value for a, on the order of 0.02. There is, therefore, no risk that the efficiency will become poor, unless the ratio u/v of the speed at the surface to the wind speed is extremely large or extremely small in relation to unity. The second case is not likely to occur in practice, since one always attempts to obtain a speed u which is much higher than the wind speed. From the standpoint of efficiency, it therefore seems necessary to retain values for the ratio u/v which are not too high. This problem will be discussed further later on.

There are two possible solutions which involve surfaces moving perpendicular to the wind. The more common of the two consists in arranging the movable surfaces radially around an axis parallel to the wind. This is the solution used by the old windmills for grinding flour seen in the French countryside. This model has advantages in that all the blades work in an identical manner in the wind and computation of its characteristics is relatively simple; thus it is the only model used in current projects involving high-power wind engines.

In another solution, the blades are arranged in the form of a revolving cylinder, around a rotational axis which is thus vertical, and consequently perpendicular to the wind. Devices of this type are sometimes called "wind turbines," and some of them are equipped with a system of fixed blades or a "distributor" around the movable blades, whose function is to steer the wind in a direction assuring maximum efficiency before it enters the movable blades.

The theoretics of this type of device have not yet been firmly established. A turbine with flat blades positioned in the wind as shown in Fig. 7 turns in the direction of the arrow f, while logically the action of the wind on the blades it strikes first should tend to make them turn in the opposite direction. It therefore seems that the wind leaving the wheel on the opposite side, after having passed through it a first time, produces the motive force. The wheel in rotation probably acts as a solid cylinder in relation to the wind and consequently produces a Magnus effect, which modifies the air flow by giving it an asymmetrical configuration such as that shown in Fig. 7b. In short, the wind must therefore enter through portion *ab* of the circumference without producing much work, perhaps even creating an opposing force, and it must leave by portion *bc*, producing useful work. The blades in portion *ca* are struck by the wind almost perpendicularly and exert a considerable braking force. Fortunately, the incurvate shape of the blades, which is favorable both to the entrance of the wind at portion *ab* and its exit from portion *bc*, is also favorable to the action of the wind on the blades in portion *ca*, since the blades offer a convex surface with less resistance to the wind than a flat or concave surface.

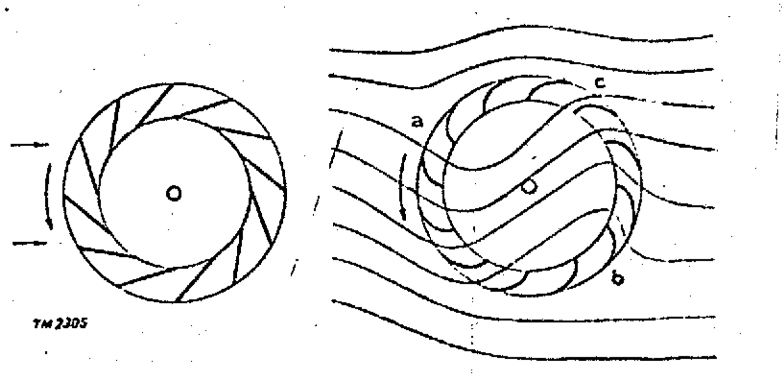

Fig. 7. Left: action of wind on a turbine with flat blades. Right: probable configuration of flow through a turbine, taking the Magnus effect into account.

Nevertheless the useful force exerted on the shaft appears to be the difference in a given number of opposing forces exerted on various parts of the wheel, with the result that the power supplied by wind turbines is much lower than that produced by classical windmills sweeping the same surface area. However, it should be noted in all fairness that this drawback may become a considerable advantage from the standpoint of automatic speed limitation. The drive force and the opposing force exerted on a single wheel undoubtedly do not vary according to the same principle as a function of the wind speed, and it is possible that the opposing force may become predominant for high winds. The operative shaft power must therefore reach a limit fairly quickly, and it is a fact demonstrated by experience that these turbines do not overspeed in high winds, as do ordinary windmills, for example. Some of these turbines would thus be able to continue to operate without surveillance or adjustment under the most violent winds occurring in our geographical area, and this basic characteristic alone is enough to justify their construction.

The fact nevertheless remains that these turbines do present a considerable surface area to the wind, and the horizontal stresses which occur during storms would thus necessitate extremely solid supports and foundations. Current wind devices seldom exceed five to six meters in diameter, and a diameter as wide as ten meters is used only very rarely. In spite of these dimensions the power supplied is no more than a few horsepower in strong winds.

Various inventors have attempted to correct the poor efficiency of the vertical axis wind turbine by eliciting a motive force from that part of the wheel which was formerly passive or resistant. This result can be obtained by a considerable increase in the rotation speed, which presupposes the use of contoured blades with excellent aerodynamic characteristics. If the tangential speed of the blades u (Fig. 8) is high in relation to the wind speed v, the relative speed w shifts to one side of the tangent to the path of the blades only by a small angle. Thus each of these blades a, articulated around a longitudinal axis b, need /81
only be provided with a suitable device enabling them to make a slight oscillatory movement so that they will follow, close to the angle of attack, directional changes in the relative speed w,

so that each of the blades will always be supplying useful work, even when it is moving against the wind.

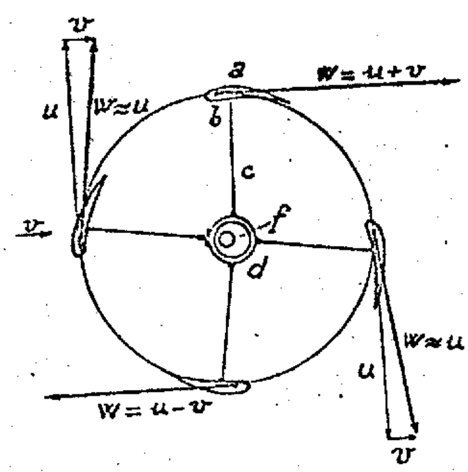

Fig. 8. Specific high-speed turbine with blades controlled by rods and eccentric wheel.

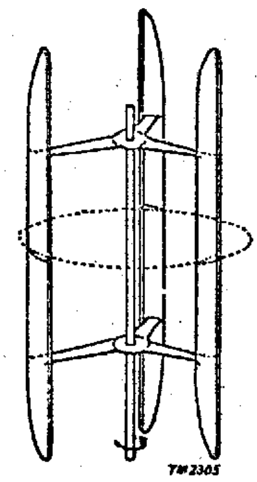

Fig. 9. Possible configuration for a specific high-speed vertical axis turbine with fixed blades.

In Fig. 8, the kinetic device consists of small rods *c* attached to a ring *d* rotating around an eccentric fixed wheel *f*. It is possible, however, to construct a similar wind engine with fixed blades. The tangential speed *u* need only be given an extremely large value in relation to the wind speed *v*. The relative speed *w* thus will shift only a few degrees to one side or another of the tangent and, if the front of the profile is adequately rounded, the blades are able to remain fixed while continuing to lift at all points along their trajectory. The wind engine is thus reduced to a small number of vertical blades integrated by means of side-bars or arms. Fig. 9 schematically shows one possible model for a wind engine of this type. In spite of their resemblance to panemones, these wind engines have a totally different mode of operation. Their efficiency is excellent and their tangential speed may be as high as several times that of the wind. They are thus perfectly suited to use in high-power installations. Nevertheless, since until now these wind engines have been built only for industrial applications, we will eliminate any further discussion and move ahead to a type of device which gave rise to considerable expectation about 25 years ago: the Flettner rotors.

Flettner Rotors

A cylinder rotating around its axis with sufficient speed, positioned transversally to an air current, is known to produce an asymmetric pattern in the air flow which is translated into a thrust perpendicular to the direction of flow (Magnus effect). A rotating cylinder of this type thus behaves as an airfoil surface. Flettner conceived of the idea of using these cylinders or "rotors" to constitute sails for ships or blades for wind engines (Fig. 10). Apparently the results were not particularly satisfactory. At any rate, an American inventor later proposed to use Flettner rotors to construct a vertical axis high-power turbine [1]. Each turbine consisted of 15 to 40 vertical rotors with a unit weight of 50 tons, moving along a circular track about one kilometer in diameter, at a spacing of ten meters. Each rotor was composed of a flanged aluminum sheet supported by a duralumin armature, and each was given its initial rotation movement by an electric motor. Wind then exerted a force on each rotor which resulted in the movement of the cart along the circular track. The wheels of each cart drove an electric generator whose current was collected by means of sliding contacts on a circular contact rail. To keep the rotation continuous it was necessary to reverse the direction of rotation of each rotor twice for each circuit around the track. The inventor estimated that each rotor would be able to produce 1,000 kilowatts of power under favorable winds.

A full-sized rotor was to be assembled on stable foundations at West Burlington to confirm the results obtained in a wind tunnel using a small-scale model. At that time (1931) it was estimated that an installation of this type would cost $40 per kilowatt for a power capacity of 40,000 kW. This original installation apparently never went beyond the preliminary research stages.

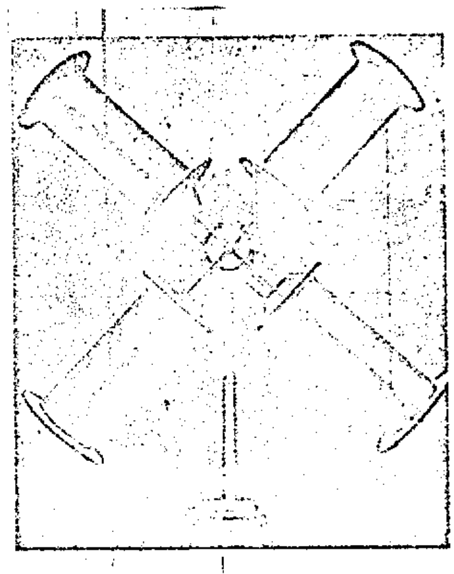

Fig. 10. Wind engine consisting of four Flettner rotors.

Although this review of panemones and wind turbines is still incomplete, we must now move on to a more detailed discussion of the classical wind engine with horizontal shaft and radial blades.

Engine with Horizontal Shaft and Radial Blades

The present article will not deal in detail with windmill theory, which was apparently first established in 1927 by A. Betz of the Institute of Göttingen [2]. Instead, only the essential points of this theory will be discussed.

A wind engine acts as an obstacle which decreases the speed of the wind from its upstream value V to a residual downstream speed v (Fig. 11). This decrease in speed begins to occur before the wind reaches the obstacle, with the result that the wind arriving at the blades is no longer at speed V but a lower speed V_m, which obviously falls between V and v. It can easily be demonstrated that

$$V_m = \frac{V + v}{2} \quad .$$

For a wind engine with a given diameter sweeping a surface area S, and wind with a speed V, the power extracted from the wind

varies with the residual speed v, that is with the ratio $\frac{v}{V} = k$. /82
This power may be written in the form

$$W = \rho \frac{S\ V^3}{4} (1 + k)\ (1 - k^2)$$

The power is thus at its maximum for $k = 1/2$, or for a speed equal to one-third the initial speed, and it thus assumes the value

$$W_{max} = \frac{8}{27} \rho\ S\ V^3 = 0.296\ \rho\ S\ V^3.$$

This maximum power, therefore, is only 16/27 of the total power $1/2\ \rho\ S\ V^3$ which would be contained in an air current at a speed V flowing over the surface area S of the wind engine. This result does not contradict our earlier statement that the efficiency will equal unity for a profile without drag. It can be explained by the fact that the blades are struck, not by a wind at speed V, but by a wind at a speed V_m whose value is only 2/3 that of V, and by the fact that the power W_{max} corresponds to that contained in a current at a speed 2/3 V sweeping surface area S, and experiencing a drop in pressure as it passes through the wheel.

$$\frac{1}{2} \rho\ (V^2 - v^2) = \frac{4}{9} \rho\ V^2$$

In practice, with $\rho = 1.25$ kg/m^3, and assuming the efficiency to be 0.80, it can be seen that:

$$W_{max} = 300 \text{ W/m}^2$$

for a 10 m/sec wind.

We will reiterate the following conclusions, which are still little recognized at present even though windmill theory already dates back twenty years.

1) The power produced by a wind engine is independent (at least on first analysis) of the surface area and the shape of the

blades. It depends only on the surface area of the circle swept by the blades.

2) The wind strikes the blades at a speed which is much lower than that at which it was traveling some distance upstream from the blades. Under the most favorable theoretical conditions, this speed is only 2/3 that of the wind.

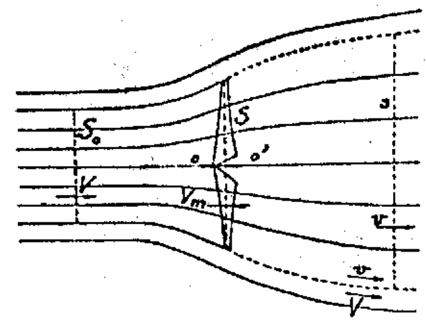

Fig. 11. Air flow through a wind engine with radial blades.

3) The maximum power which can be obtained, with a wind engine sweeping a surface area S in a wind at speed V, is only about half the theoretical power $1/2\ \rho\ S\ V^3$ contained in the wind. Thus any attempt to extract more power will be futile. The power actually supplied must thus be compared to this maximum power W_m in order to estimate the efficiency of a wind engine.

It has just been stated that the power of a wind engine is independent of the surface area, the shape, and, consequently, the number of the blades. This is true only for perfect profiles without friction. In this case, only the product of the number of blades multiplied by the rotation speed will figure in the calculations. The same amount of power may thus be obtained either with a large number of blades of large dimensions turning at slow speeds (American windmills) or with a small number of blades of small dimensions turning at high speeds (modern windmills). In practice, all profiles are affected by drag, and a formula for the efficiency was established earlier which makes use of the inverse of the aerodynamic ratio and the ratio u/v. On the basis of this formula alone, the American type of wind engine, with its low u/v ratio, would seem to have the advantage. However it can easily be seen that, if a is given a sufficiently low value by using a profile with high aerodynamic efficiency, the u/v ratio can be considerably increased and consequently only a small number of blades may be used without lowering the efficiency below acceptable levels. With an aerodynamic efficiency of 50, for example (a = 0.02), the efficiency would still be close to 80% for a u/v ratio equal to ten.

The advantages of using a small number of blades are obvious: the blades are narrow, and therefore light and relatively low in construction cost; they are highly resistant to storm winds; it is easier to install adjustment devices (swivelling blades); and finally, the rotation speed is higher and there is less engine torque to be transmitted through the gear trains. The sole drawback is the low starting torque, which may be inadequate to overcome the friction and set the device in motion. This is not very serious, however, when the wind engine is intended to drive electric generators, whose starting torque is minimal, especially when they are equipped with bearings. Furthermore, in the extreme case where the wind engine is unable to start by itself, there is no reason that it cannot be "boosted" by means of an auxiliary engine, or using its own generator powered by an external source of current.

The slight inadequacy of the efficiency may always be compensated for by an insignificant increase in the diameter of the blades.

In short, a wind engine with only a few narrow blades thus seems to be particularly well-suited for large installations; and in fact the high-power wind engines which have most recently been designed do possess only two, three, or at the most, four blades. In principle these devices differ very little from the classical four-blade Dutch windmill. One might wonder why it has taken until the last few years to produce high-power wind engines (1,000 kW), and why almost all past attempts were frustrated. The answer to this question must be sought in considerations of an economic rather than a technical nature.

The technical problems involved in the design of high-power engines have virtually been solved. One of the most difficult problems involved transmitting the engine torque through the shaft, upon attainment of any sizable amount of power. The power of a wind engine varies as a function of the square of its diameter, while the rotation speed is in inverse proportion to this diameter. Furthermore, the blades must be all the more cantilevered on the shaft since they are usually inclined in the direction of the wind. For these two reasons the shaft and its auxiliary parts (bearings, etc.) rapidly increase in bulk, weight and cost. The multiplying gear train must thus transmit an increasing amount of torque at a higher and higher multiplication ratio, and its cost eventually constitutes a large fraction of the total price.

To correct this difficulty, it has been proposed that the solid cylindrical shaft be abandoned and replaced by a hollow assembly in the form of a prismatic or pyramidal lattice supported by rotating rings turning on rollers. This is the solution which was adopted by the U.S.S.R. for a 100 kW test installation built /83 at Balaklava [3]. The first wheel of the gear train is attached directly to the blades, so that no torque is transmitted to the shaft. The disadvantage in this arrangement is that the gear wheel participates in the elastic deformation of the blades caused by the lack of homogeneity of the wind, and consequently attacks its pinion under poor conditions. Furthermore, splash lubrication is difficult.

It has also been proposed that the gear train be eliminated and the rotor for the electric generator be mounted directly on the blades. This solution was adopted by Kleinhenz in Germany for its 10,000 kW aeroelectric plant project (Fig. 12). Given the slow rotation speed, this solution leads to very wide-diameter electric generators which are realizable in practice only in the form of alternating generators. In the German project [4], for example, the diameter of the 12,500 kVA alternator was 28.5 meters, so that it could contain the 500 poles producing the very slow rotation speed of 12 rpm. The elastic deformation of the blades makes it necessary to provide a considerable air gap (25 mm in the present case) which has an unfavorable effect on the efficiency. Finally, a wide-diameter generator is difficult to protect from bad weather, unless the expedient is taken of placing it within the body of the wind engine; the latter must thus assume exaggerated dimensions.

Two other classical solutions which may offer attractive possibilities should be noted. One consists in transmitting the energy from the blades to the receiving machine by means of a pneumatic transmission using underpressure air. The originality of this procedure rests in the fact that the underpressure air is not produced by means of supplementary devices, but by the blades themselves, using static devices functioning as ejectors. In the schematic example shown in Fig. 13, each blade is hollow, and its leading edge is split for a given length close to its tip. When the wind engine turns, a relative wind which strikes the blade at an extremely high speed will produce a considerable depression in the wake behind the slit, and, consequently, a forceful suction of the air contained within the blades. All the blades feed at their lower part into a hollow hub which communicates with a suction conduit terminating in an air turbine. On its shaft the latter translates the pneumatic energy expended in the wind engine into mechanical form. Since the depression produced is relatively moderate, but the air flow rate is considerable, the air turbine may be of simple design, with one or two large-diameter stages, and its cost is no greater than that of a multiplying gear train of the same power capacity. In addition there is the advantage that with an automatic transmission the speed of the electric generator is not strictly linked to that of the blades, as is the case with a mechanical transmission. Thus it is possible to build installations using synchronous generators operating at constant speeds which at the same time permit the wind engine to turn at a variable speed, proportional to that of the wind, thus assuring maximum efficiency.

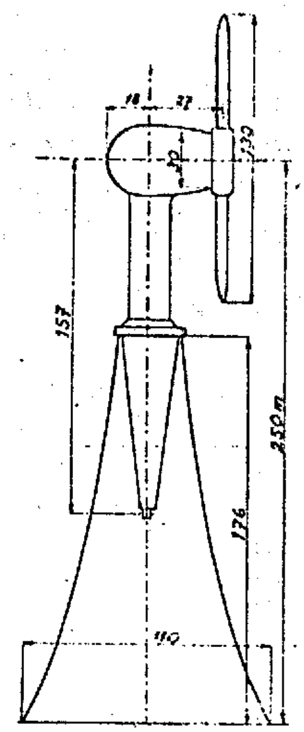

Fig. 12. 10,000-kW wind engine project, after Kleinhenz.

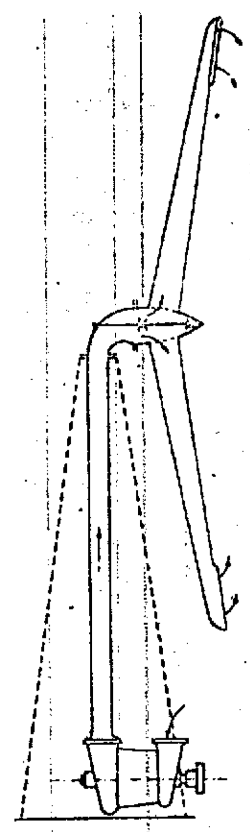

Fig. 13. Wind engine with pneumatic transmission. The air sucked in by ejectors (1) mounted at the tips of the blades (2) operates an underpressure air turbine (3) which drives the receiving machines.

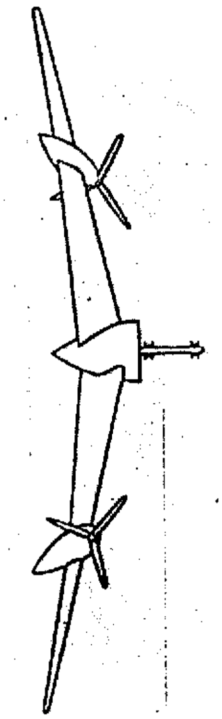

Fig. 14. Cascade wind engine.

Another method of eliminating transmission of torque by the shaft consists in mounting a small-diameter secondary wind engine on each of the blades of the primary wind engine, inclining the secondary engine so that it is struck head on by the relative wind received by the primary blades during their rotation (Fig. 14). The diameter of these secondary wind engines is calculated so that the power they produce under the action of the relative wind will be equal, except in regard to efficiency, to that supplied by the primary wind engine under the effects of the actual wind. The advantage of this procedure is that the relative wind is always much greater than the actual wind, and that consequently the diameter of the wind engines can be extremely low, enabling them to turn at a very high speed. This is illustrated by the example of a 1,000-kW wind engine designed for a wind speed of 10 m/sec. The primary wind engine would have three blades 72 meters in diameter turning at 21 rpm. To collect the same amount of power, one need only mount a secondary wind engine only 2.65 m in diameter 26 m from the center end of each blade; these secondary wind engines, struck by a relative wind at 60 m/sec, will produce 333 kW, rotating at 1,730 rpm. Thus by simply adding three small wind engines similar in design to helicopter airscrews to the primary wind engine, full power can be recovered, not at 21, but at 1,730 rpm, a speed which can be used directly to drive electric generators. The power of the secondary wind engines can be transmitted to a high-speed shaft concentric to that of the primary wind engine, for example by means of bevel gears and radial shafts mounted within the blades, or the secondary wind engines may supply power directly to electric generators connected in parallel. In spite of the necessity to divide the power among several generators, the solution proposed is no more costly than the classical gear train solution, and the model is much lighter. Moreover, there is no reason not to appropriate part of the low-speed power from the shaft of the primary wind engine. A wind engine may thus be projected which would use a rod and crank to supply direct power to a low-speed pump, and which would have a small dynamo driven by a small mill on each of its blades, the whole designed to provide illumination.

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